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Aircraft Surface Coatings Summary Report

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Aircraft Surface Coatings Summary Report

Staff of Boeing Commercial Airplane Company
Boeing Commercial Airplane Company
Seattle, Washington

Prepared for
Langley Research Center
under Contracts NAS1-14742 and NAS1-15325



National Aeronautics
and Space Administration

**Scientific and Technical
Information Branch**

1983

FOREWORD

This document summarizes work on aircraft surface coatings performed under Contracts NAS1-14742 and NAS1-15325. The surface coatings project was one of the principal tasks within the Energy Efficient Transport (EET) element of the Aircraft Energy Efficiency (ACEE) program administered by NASA-Langley Research Center. The NASA technical monitor was D. B. Middleton.

The Aircraft Surface Coatings project was conducted within the Preliminary Design department of the Boeing Commercial Airplane Company Vice President-Engineering Organization. Avco Systems Division was a major subcontractor. Principal participants were:

Boeing	Glen W. Hanks	Program Manager
	Richard L. Kreitinger	Surface Coatings Project Manager
	Robert P. Thierry	Materials Technology
	Russell R. Bowen	Materials Technology
	Leonard R. Elvigan	Materials Technology
	Walter A. Blissell	Aerodynamics Technology
	Dezso George-Falvy	Aerodynamics Technology
	Herman R. Gelbach	Systems Technology
	Martin J. Omoth	Systems Technology
	John S. Kautzky	Economic Analyses
	Reese H. Kimble	Economic Analyses
	Thomas J. Kelly	Manufacturing Engineering
	Samuel Whitworth	Customer Support
Avco	R. M. Rouleau	Project Manager
	K. M. Jacobs	Project Manager
	J. G. Alexander	Principal Investigator
	J. S. Johnson	Principal Investigator

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The project is indebted to Jim Hall of the Langley Terminal Configured Vehicle Program Office (TCVPO) and the personnel who participated in the drag-measurement flight tests for their expertise and total cooperation.

Principal measurements and calculations used during this study were in customary units.

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SUMMARY

A study was made to find suitable materials for external surface coatings on jet transports. The primary objective was to identify, through test, a smooth, durable coating that would reduce airplane drag and conserve fuel. A corollary objective was to reduce airplane maintenance costs.

Liquid spray-on elastomeric polyurethanes were found to best meet the severe requirements imposed by the transport operating environment. Two commercially available elastomeric polyurethanes, CAAPCO B-274 and Chemglaze M313, were tested extensively and compared to two coating systems (Astrocoat Type I and Corogard) already in commercial use. It was found in airline service evaluations that, if properly applied, these coatings, when applied to high-erosion areas such as wing and tail leading edges, have a maintenance-free service life of about 2 years in normal airline utilization.

Flight tests were conducted on the NASA B737 Terminal Configured Vehicle (TCV) to measure the effects of coatings on airplane drag. It was determined that, at a typical cruise condition, CAAPCO reduced airplane drag 0.2% when applied to the bare wing upper surface and that rough Corogard (160 μ in roughness) increased drag by about the same amount. The Corogard tested was somewhat rougher than fleet average (130 to 150 μ in). As a result of these tests, efforts are being made to further reduce roughness of surface coatings on new airplane applications. Replacing rough Corogard with CAAPCO on the wing upper surface and replacing enamel with CAAPCO on the empennage surfaces would produce a total airplane drag of about 0.55%.

During one flight in the B737 TCV test series, a severely eroded leading edge was simulated with a 7.6-cm (3-in) strip of No. 50 metallic grit glued onto the leading edge ahead of the wing test section. This strip caused a drag increment of approximately 0.3%. Combining this with the total airplane drag of 0.55% gives the possible total drag reduction, 0.85%. A cost/benefit analysis based on the 0.85% drag reduction indicated a net benefit per airline B737 of up to \$10 000 per year with fuel costs at 26.4¢/L (\$1.00/gal).

Coating only leading edges for erosion protection would not be significant in terms of fuel savings; however, in severe cases, low-speed handling qualities might be improved and the costs of buffing or replacing leading-edge parts might be avoided.

Coatings applied to structural skins must protect against corrosion. Laboratory tests of elastomeric polyurethanes, with a topcoat of polyurethane enamel for added protection against hydraulic fluid spills, indicated that the polyurethanes would provide very good corrosion protection; however, the long-term effects of environment on corrosion protection are unknown. It is recommended that industry pursue any additional corrosion-protection investigations necessary to fully qualify these coatings for application to the jet transport fleet.

INTRODUCTION

Investigations of surface coatings for airplane drag reduction were initiated in August 1977 under Contract NAS1-14742 and were completed in July 1982 under Contract NAS1-15325. Both contracts were administered by NASA-Langley Research Center as a part of the Aircraft Energy Efficiency (ACEE) program.

The four areas of investigation during the surface coatings study are shown in Figure 1. Liquid spray-on coatings and various film/adhesive systems were selected from the large number of available materials for initial screening and for more rigorous advanced testing in the laboratory. The best film/adhesive systems had poor erosion durability in leading-edge applications and were judged to be impractical for application to large surfaces with compound curvature. For these reasons, films were eliminated from further study.

The three best candidate coatings (elastomeric polyurethanes) were subjected to further laboratory testing to verify their compatibility with the operating environment of commercial transports. They also were evaluated over extended periods on the leading edges of two 727 airplanes in commercial service with Continental Airlines and Delta Air Lines.

During the final phase of the program, flight tests were conducted on the NASA B737 Terminal Configured Vehicle (TCV) to measure the drag effects of the coatings compared to conventional surface treatments. Also, the drag effect of a badly eroded leading edge (simulated by adding metallic grit) was measured.

A cost/benefit analysis was made and updated as additional test results became available. Final reports (refs. 1, 2, and 3) were published at the conclusion of each phase of the program.

NOTE:

Certain commercial materials are identified in this document in order to specify adequately which materials were investigated in the research effort. In no case does such identification imply recommendation or endorsement of the product by NASA or Boeing, nor does it imply that the materials are necessarily the only ones or the best ones available for the purpose.

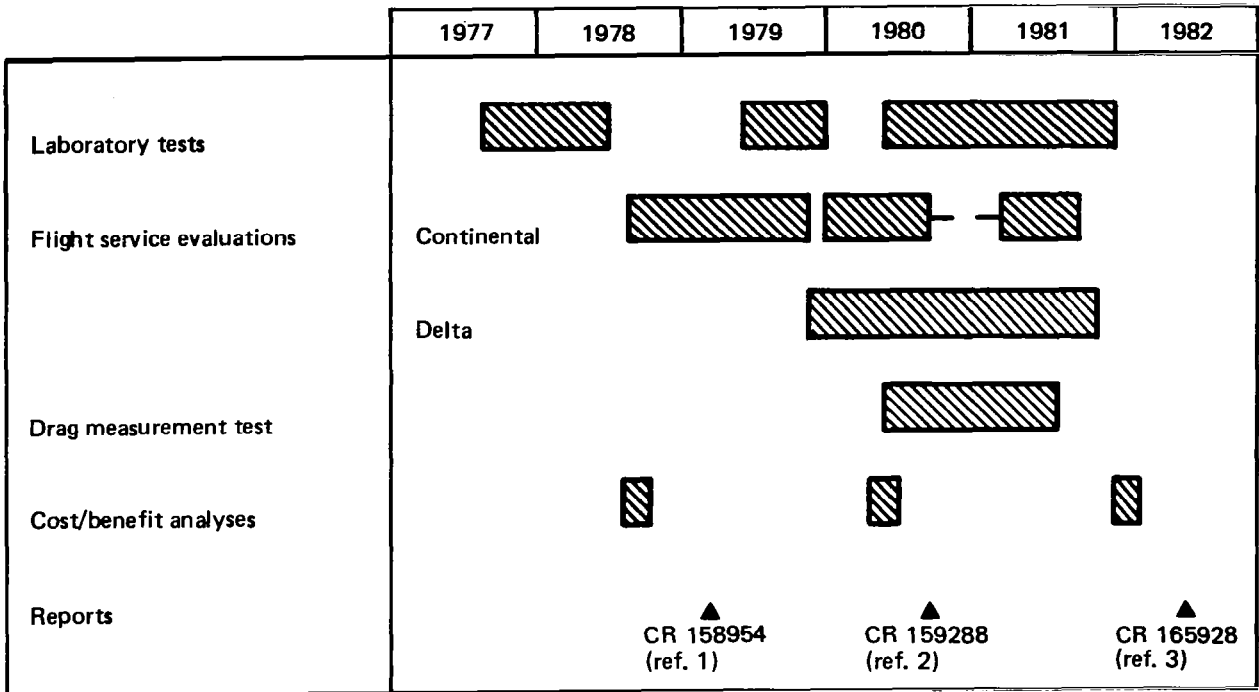


Figure 1. Aircraft Surface Coatings Program

LABORATORY TESTS

Nine liquid spray-on coatings, 11 films, and 13 adhesives were selected for evaluation from the large number of available products. The liquid coatings and 60 film/adhesive combinations were then subjected to the laboratory screening tests listed in Figure 2. The liquid coatings and 16 film/adhesive systems were retested to more rigorous requirements to produce the 3 coatings and 4 film/adhesive systems of Figure 2 as the best candidate materials.

The candidate coatings and films met smoothness criteria; however, the films were found to be much less durable than the coatings in high erosion applications, such as leading edges. Furthermore, the application of films to large surfaces, especially those with compound curvature, was not considered to be economically feasible. Therefore, the remainder of the work was concentrated on the three liquid spray-on coatings: CAAPCO B-274, Chemglaze M313, and Astrocoat Type I, all of which are elastomeric polyurethanes. The testing that led to this decision is reported in Reference 1.

Further testing of the three elastomeric polyurethane coatings was conducted to verify their compatibility with the operating environment of airline transports. These tests are described in detail in References 2 and 3. Some of the more significant results are summarized below.

Rain Erosion. A summary of rain erosion test results is presented in Figure 3. The tests were run in the Avco Systems Division facility (solid symbols), which produced 0.7-mm (0.028-in) diameter rain drops and in the Air Force Materials Laboratory (AFML) facility (open symbols), which produced 1.8-mm (0.07-in) rain drops. All tests were at 224 m/s (500 mi/h) and with a rain rate of 2.54 cm/h (1 in/h).

The durability of 12-mil CAAPCO and Chemglaze coatings, tested in the Avco facility, was much greater than the bare aluminum substrate or any of the 5-mil films (fig. 3a). The average time to when failure of the four CAAPCO specimens started to occur was 402 minutes, which is roughly equivalent to 6000 flight-hours in airline service. The AFML tests indicated that the coating thickness could be reduced to about 9 mil without sacrificing erosion life.

Erosion tests performed on bare and coated composite substrates (fig. 3b) revealed that the bare materials had a very short erosion life. Although the coatings were beneficial, even the best combination (CAAPCO over fiberglass) would begin to fail after the equivalent of about a year of airline jet transport operation.

Icing. Icing tests were conducted on a model of a section of 767 wing leading-edge slat, bare and coated with 12 mil of CAAPCO or Chemglaze. The slat section was equipped with a thermal anti-icing (TAI) system, having airflow and temperature set at the values for 767 certification. It was found that the coatings had only a very slight effect on TAI system performance and the elevated temperatures, which approached 120°C (250°F), did not affect the coatings.

Ice shed during deicing tests did not pull off any patches of coating. During this phase of testing, part of the model was overcoated with a thin layer of icephobic silicone grease. When the TAI system was turned on, ice was dissipated from that area in about one-quarter of the time required for the area not overcoated.

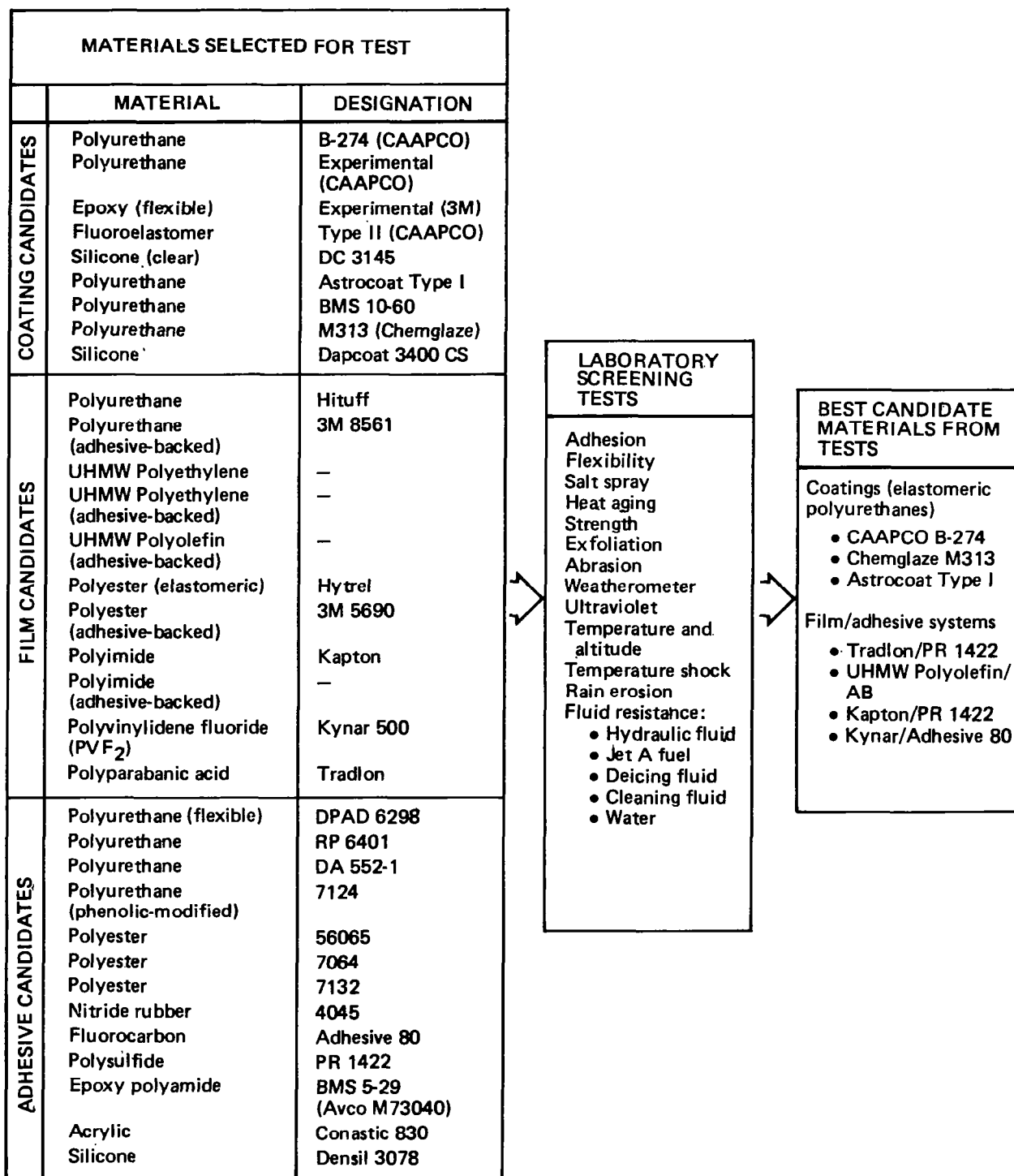
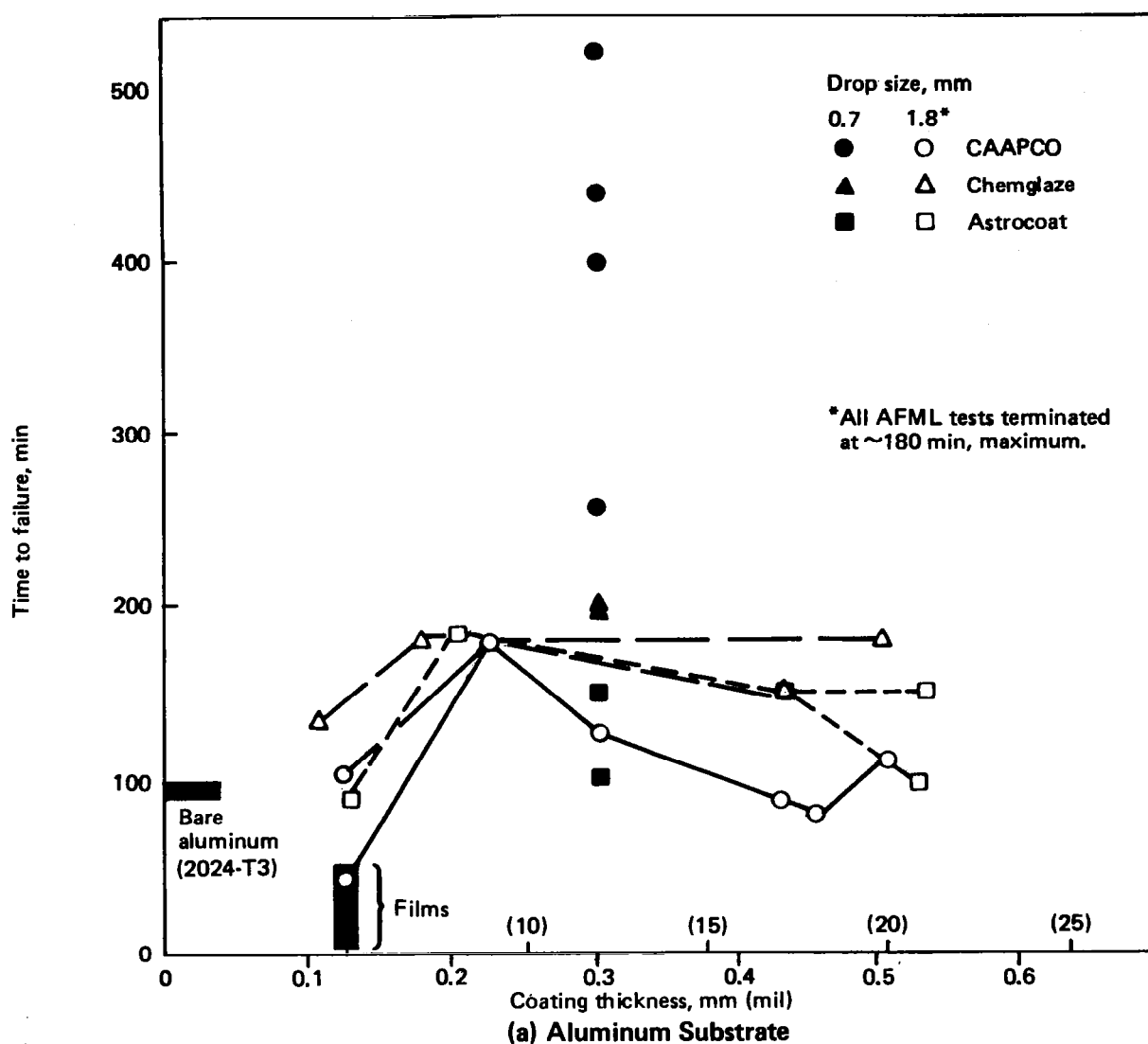


Figure 2. Laboratory Screening Process for Selection of Best Candidate Materials



COATING	TIME TO FAILURE, min			
	BARE	CAAPCO	CHEMGLAZE	ASTROCOAT
Kevlar	1.4	16.8	32.4	24.5
Fiberglass	8.9	90.2	38.4	35.6
Graphite	12.8	39.5	38.7	43.1
Kevlar-graphite	1.4	17.5	34.4	32.1

Coating thickness = 0.23 mm (9 mil); drop size = 1.8 mm

(b) Composite Substrates

Figure 3. Summary of Rain Erosion Tests at 224 m/s (500 mi/h)—Rain Rate, 2.54 cm/h (1 in/h)

Hydraulic Fluid Exposure. The elastomeric polyurethane coatings are susceptible to synthetic-type hydraulic fluids, such as Skydrol or Hyjet Type IV; however, CAAPCO is much more resistant to attack than either Chemglaze or Astrocoat. It was found that a topcoat of polyurethane enamel (BMS 10-60) provided additional protection from hydraulic fluid to each of the coatings. The enamel topcoat would be applied to areas aft of the front spar, as protection against runback from fluid leaks in leading-edge systems. The topcoat over the flexible coating is not durable in areas of high erosion and, therefore, would not be suitable for leading-edge application.

Electrical Phenomena. It was determined through test and analyses that coatings from the leading edge to rear spar, with a polyurethane enamel topcoat on the inspar region, would not cause precipitation static (P-static) interference with communication and navigation equipment aboard the airplane.

The effects of coatings on lightning charge dissipation must be considered individually for each airplane model. Airplanes with wing fuel immediately adjacent to wing-mounted engines should be subjected to analyses and possibly tests to determine if there is enough structure in that area to dissipate a maximum charge without creating a possible source of fuel ignition. Potential hazards can be avoided by omitting inspar coatings in that immediate area or by adding conductive material to reduce the coating dielectric strength.

Corrosion Protection. Salt-spray, filiform, and dynamic tests were performed on coated specimens to evaluate corrosion protection characteristics. Three test coatings—CAAPCO, Chemglaze, and Astrocoat—each with a topcoat of polyurethane enamel, were compared to three control coatings currently in use. The control coatings were: enamel over an epoxy primer, enamel over a polysulfide primer, and Corogard over an epoxy primer. All specimens were of 7075-T6 aluminum alloy plate with countersunk titanium fasteners.

Fasteners in the salt-spray and filiform test specimens were rotated prior to testing to break the coating seal in order to compare corrosion progress in case of a fractured coating seal. One set of specimens was exposed to salt spray for 90 days; the other set (filiform test) was exposed to hydrochloric acid for 1 hour, then placed in an elevated-temperature high-humidity environment for 90 days. The specimens were disassembled and examined for corrosion at fastener locations. Progressive corrosion ratings of none, trace, moderate, medium, excessive, and extremely heavy were assigned. Test results are summarized in Table 1.

Under normal aircraft structural flexing, some slight movement of fasteners occurs relative to the attached structure. Rigid coatings tend to fail at these locations and create a path for corrosion penetration. The flexible elastomeric test coatings absorb the relative movement and retain their seal over fastener heads. The dynamic tests (described in ref. 3) were designed to evaluate this protective mechanism of elastomeric coatings by combining corrosion-inducing factors with cyclic stress loading of the specimens. The dynamics tests, therefore, were considered to be the most significant of the three types of corrosion tests conducted. The dynamic tests consisted of a series of five parts conducted in sequence:

- | | | |
|----|---------------------|------------|
| 1. | Condensing humidity | 2 weeks |
| 2. | Weatherometer | 1 week |
| 3. | Cyclic loading | 250 cycles |
| 4. | Salt spray | 1 week |

Table 1. Summary of Salt-Spray and Filiform Corrosion Tests

COATING	SALT SPRAY		FILIFORM	
	COUNTERSINK	HOLES	COUNTERSINK	HOLES
Control				
Enamel/epoxy primer (BMS 10-60/BMS 10-79)	Trace	None	Trace	None
Enamel/polysulfide primer (BMS 10-60/PR 1432)	Trace	None	Trace	None
Corogard/epoxy primer (EC 843/BMS 10-79)	Trace	Trace	Trace	None
Test				
Enamel/CAAPCO/epoxy primer (BMS 10-60/B-274/BMS 10-79)	Trace Moderate Trace	None None None	Trace Moderate Moderate	Medium Trace Trace
Enamel/Chemglaze/epoxy primer (BMS 10-60/M313/BMS 10-79)	Trace Trace Trace	None Trace Trace	Moderate Moderate Moderate	Medium None None
Enamel/Astrocoat/epoxy primer (BMS 10-60/Type I/BMS 10-79)	Trace None Trace	None None None	Moderate Moderate Trace	Trace Moderate None

Rating scale:

- None
- Trace
- Moderate
- Medium
- Excessive
- Extremely heavy

5. Potentiostat

measure current flow
(corrosion penetration)

The series was repeated three times, with the cyclic loading stress level at 155 138 kPa (22 500 lbf/in²), 193 060 kPa (28 000 lbf/in²), and 241 325 kPa (35 000 lbf/in²) for the three series. The final step in each series was to determine corrosion penetration, as indicated by current flow through the coating, measured by Potentiostat.

Results of the dynamic tests, shown as Potentiostat current flow, are presented in Figure 4. The three control coatings showed positive current flow during each of the Potentiostat tests, indicating a corrosion path at fastener heads where the coatings had failed. Control coating C (Corogard), which had the lowest current flow of the control coatings, contains sacrificial aluminum particles that greatly delay corrosion attack of the substrate. None of the elastomeric test coatings (coatings I, II, and III) showed any current flow, indicating that the seal over fastener heads had not fractured during the high cyclic loads imposed on the specimens.

Although the dynamic tests showed that the test coatings have superior qualities for protecting against corrosion, the long-term effects of environmental exposure must be proved satisfactory before the industry can substitute elastomeric polyurethane dual coatings for coatings currently used to protect critical aircraft structure from corrosion.

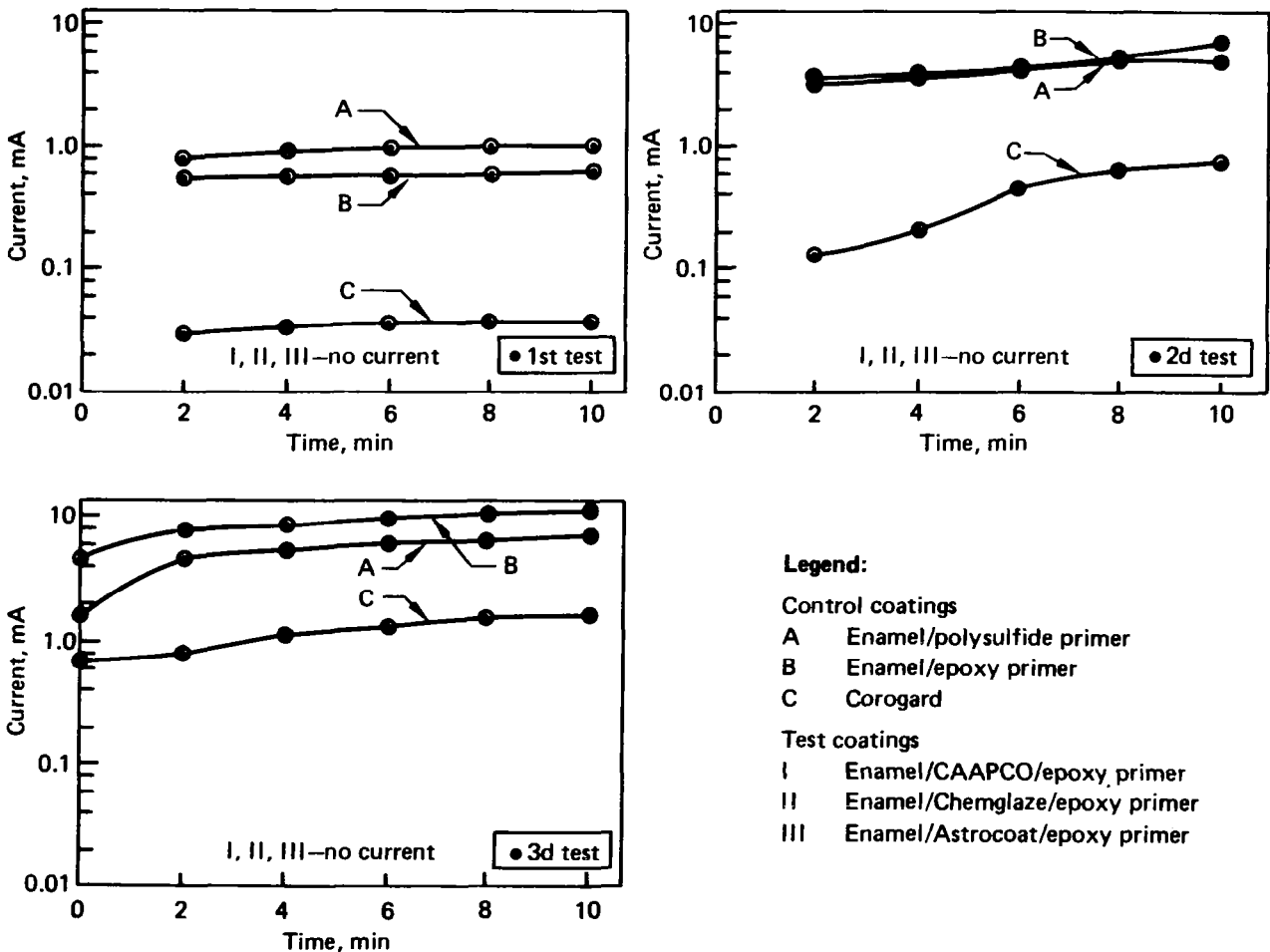


Figure 4. Dynamic Test Results—Potentiostat Current Flow Measurements

AIRLINE SERVICE EVALUATIONS

The erosion durability of CAAPCO and Chemglaze coatings on B727 airplanes in commercial passenger service was evaluated by Continental Airlines (CO) and Delta Air Lines (DL). The coatings were applied in 12-mil thicknesses to the leading edges of wing slats and the horizontal tail, as shown in Figure 5. The evaluations are fully described in References 2 and 3 and are summarized in the following paragraphs.

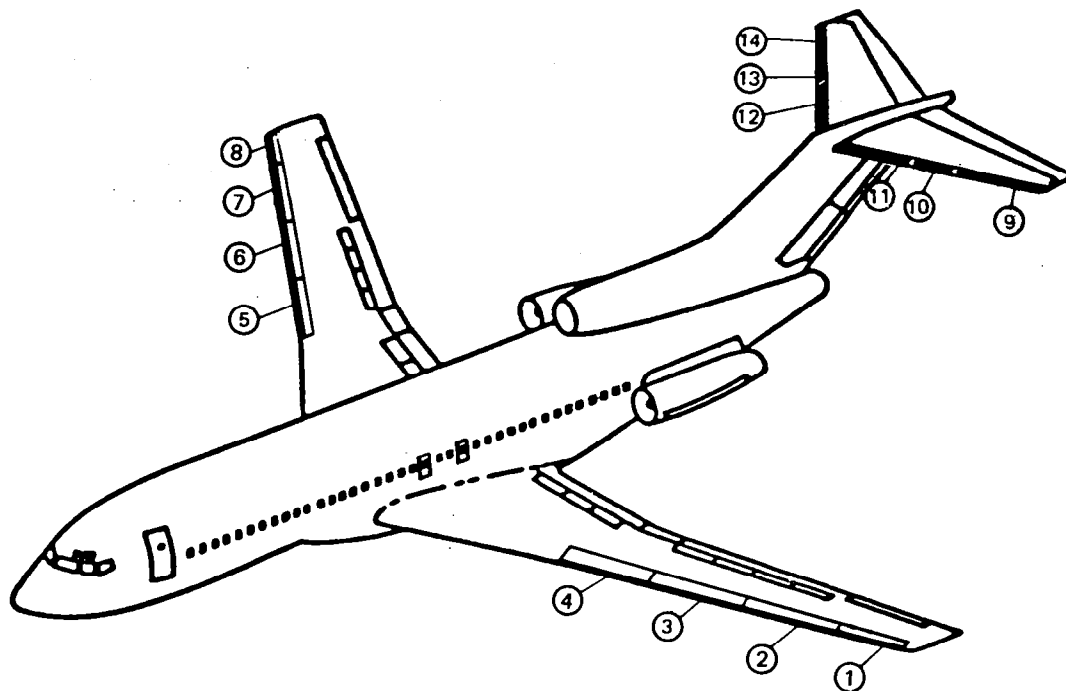
Continental. CO conducted two successive evaluations. The first was on a B727 flying the Air Micronesia route system among the Pacific islands, where average annual rainfall exceeded 228 cm (90 in). This evaluation was over a 14-month period in which 3082 flight-hours were accumulated. The second evaluation was flown over an 18-month period in which the first 11 months and 2741 hours were flown on U.S. domestic routes and the remaining 7 months were in Air Micronesia service, for a total of nearly 4900 flight-hours. For the second evaluation, a control part coated in the laboratory with panels of Chemglaze, Astrocoat, and CAAPCO was installed in the right-hand outboard horizontal tail leading-edge position to compare the durability of those coatings with that of coatings applied by the airline during normal maintenance in a hangar environment.

During the first CO evaluation, no repair or touchup was performed on the coatings. All the parts, except slat 7, showed coating damage from exposure to the severe erosion environment of the Air Micronesia route system. Slat 7, coated with Chemglaze, was observed to be free of erosion and peeling. Other Chemglaze-coated parts sustained various amounts of leading-edge erosion, but no edge peeling. Several of the CAAPCO-coated parts had edge peeled. The peeling resulted from problems with removing masking tape during coating application. Slat 4 had no edge peeling and no erosion except at the inboard end. Figure 6 shows typical examples of coating condition at the conclusion of the first CO service evaluation.

Early into the second CO evaluation, peeling began on some of the slat coatings, necessitating recoating after about 1500 flight-hours. Cause of this peeling was believed to be improper cleaning of the substrate surface prior to coating application. During the next 1200 hours, touchup of some small spots of inboard edge erosion was attempted with little success. After 2741 hours, the coatings were in generally good condition, except for minor erosion (1 to 2 cm [0.4 to 0.8 in]) at the inboard ends of parts and at a few exposed fastener heads. At that time, the laboratory-coated control part was transferred to another airplane, where its condition was observed for an additional 1200 hours.

Figure 7 shows the control part after 18 months and 4873 flight-hours. The Chemglaze and CAAPCO coatings were intact except for minor erosion of about 1 cm (0.4 in) at the inboard and outboard edges. CAAPCO retained the high gloss that was common to all three coatings at time of application. The Astrocoat panel had several spots along the leading edge where the coating had eroded down to bare metal. The exposed areas of bare metal between coating panels had begun to erode along a 5-cm- (2-in-) wide strip at the leading edge.

Delta. CAAPCO and Chemglaze coatings, applied as shown in Figure 5, were evaluated over a 2-year period on a DL B727 flying U.S. domestic routes. During this period, 6435 flight-hours were accumulated. Coatings on the left side of the airplane were applied over an epoxy primer (BMS 10-79); those on the right side were applied over a wash primer (Hughson 9924).



		DELTA AIR LINES			CONTINENTAL AIRLINES*		
ITEM		PRIMER	COATING	COLOR	PRIMER	COATING	COLOR
WING SLATS	①	BMS 10-79 (epoxy)	CAAPCO B-274	Gray	BMS 10-79 (epoxy)	CAAPCO B-274	Black
	②		Chemglaze M413				
	③		Chemglaze M413				
	④		CAAPCO B-274				
	⑤	Hughson 9924 (wash)	CAAPCO B-274	Gray	BMS 10-79 (epoxy)	Chemglaze M313	Black
	⑥		Chemglaze M413				
	⑦		Chemglaze M413				
	⑧		CAAPCO B-274				
HORIZ TAIL LE	⑨	BMS 10-79	Chemglaze M313	Black	BMS 10-79 (epoxy)	CAAPCO B-274 ⁽¹⁾	Black
	⑩	—	Uncoated				
	⑪	BMS 10-79	CAAPCO B-274				
	⑫	Hughson 9924	Chemglaze M313	Black	BMS 10-79 (epoxy)	Chemglaze M313 ⁽²⁾	Black
	⑬	—	Uncoated				
	⑭	Hughson 9924	CAAPCO B-274				

*Configuration for first Continental evaluation.
Changes in second evaluation as noted:

- (1) Outboard half only.
- (2) Inboard half bare. Laboratory-coated control part installed on outboard half with equal panels of CAAPCO, Astrocoat, and Chemglaze.

Figure 5. Coating Configurations for Airline Service Evaluations



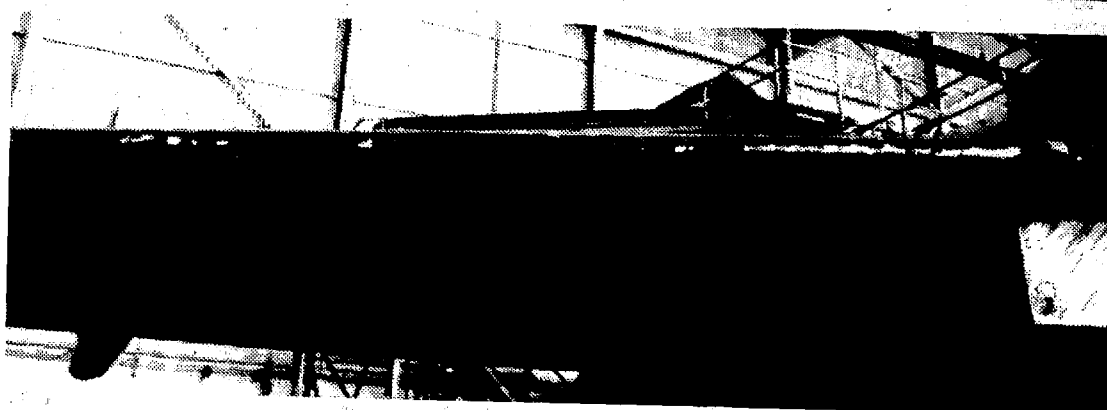
Slat 1 (CAAPCO)

- Edge peeling, two places and leading-edge erosion



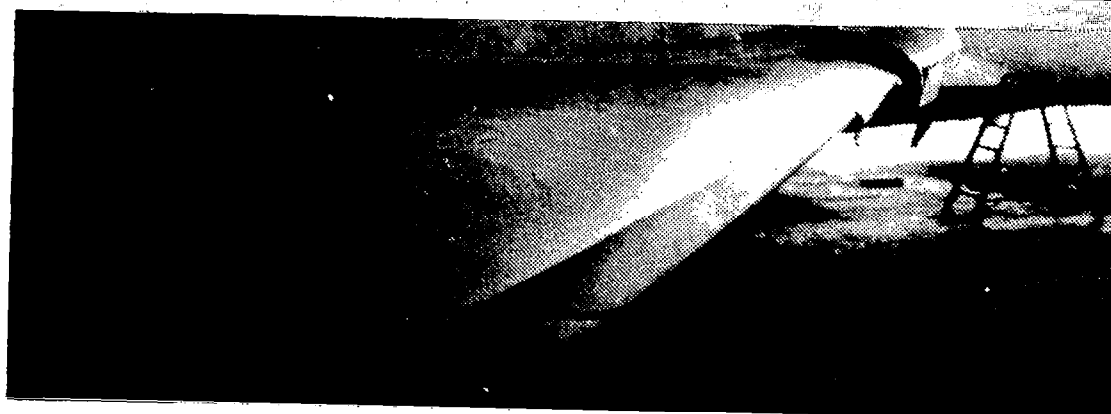
Slat 4 (CAAPCO)

- No edge peeling
- Erosion at inboard end only



Slat 6 (Chemglaze)

- Leading-edge erosion
- No edge peeling



Slat 7 (Chemglaze)

- No edge peeling
- No leading-edge erosion

Figure 6. Coating Condition at Conclusion of First Continental Airlines Evaluation (14 Months, 2600 Flight-Hours, Air Micronesia Route System)

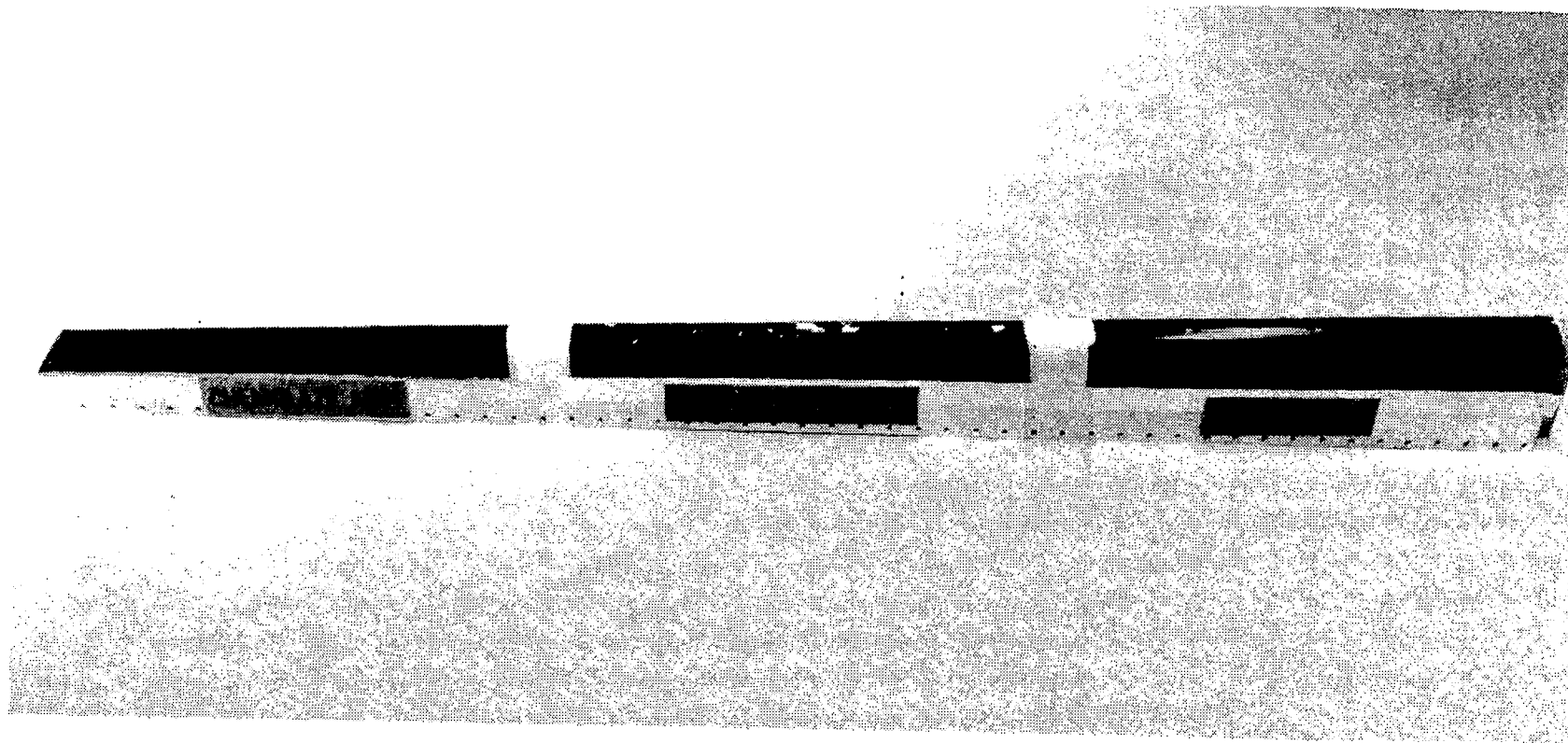
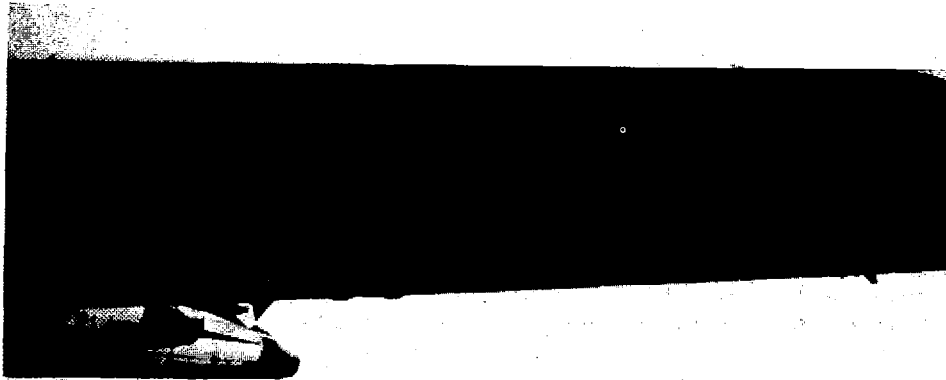


Figure 7. Three Coated Panels on Control Part After Service Evaluation

Neither coating peeled on the left side of the airplane; however, CAAPCO peeled excessively on the right side. The gray Chemglaze M413 on the wing slats began to lose gloss after about 600 hours and began to yellow from ultraviolet (UV) exposure at 2400 hours. Leading-edge erosion started shortly thereafter and became prevalent on all Chemglaze-coated slats by the end of the evaluation. CAAPCO-coated slats 1 and 4 remained in good condition throughout the evaluation. Figure 8 shows the coatings on the four left wing slats at the conclusion of the 6435 flight-hour evaluation.

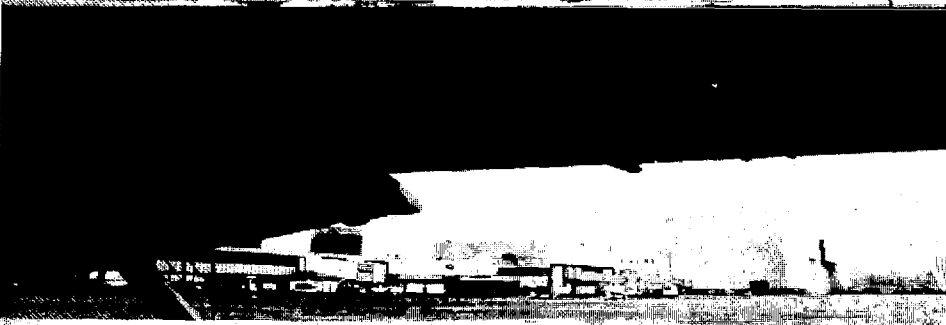
Black Chemglaze M313 on the horizontal tail showed very little deterioration. There were some erosion spots in the CAAPCO coating on the leading edge.

It was concluded from the DL evaluation that an epoxy primer base is required for good adhesion of CAAPCO coating. A UV-resistant topcoat should be applied over gray Chemglaze M413 to prevent deterioration from UV radiation. DL found that spot repairs of coatings were very difficult to perform during short turnaround periods.



Slat 1 (gray CAAPCO)

- No leading-edge erosion
- No UV discoloration



Slat 2 (gray Chemglaze)

- Extensive leading-edge erosion, exposing primer or bare metal



Slat 3 (gray Chemglaze)

- Extensive leading-edge erosion, exposing primer or bare metal



Slat 4 (gray CAAPCO)

- No leading-edge erosion
- No UV discoloration

Figure 8. Coatings on Left Wing Slats After 6435 Flight-Hours—Delta Evaluation

DRAG MEASUREMENT FLIGHT TESTS

A flight test program was conducted at NASA-Langley Research Center to investigate the effects of surface coatings on airplane drag. The tests were flown on the NASA B737 Terminal Configured Vehicle (TCV), an airplane especially equipped for precision flying and data gathering. The test surface on the inboard wing was free of leading-edge devices that might influence test results and provided a representative jet transport airfoil section on which boundary layer measurements could be taken at full-scale Reynolds number.

Test Description. The test program included five flights during which five configurations were tested:

<u>Flight</u>	<u>Configuration</u>	<u>Data</u>
1	Existing paint	Boundary layer profiles
2	Bare metal surface	Section pressure distributions
3	Bare metal surface	Boundary layer profiles
3a	Bare, with rough leading edge	Boundary layer profiles
4	Corogard	Boundary layer profiles
5	CAAPCO	Boundary layer profiles

The test panels, shown in Figure 9, spanned 203 cm (80 in), beginning 66 cm (26 in) from the side of the body and extending to the proximity of the nacelles. Coatings were applied to the left wing test panel back to the 75% chord line. The right wing panel was stripped to bare metal and was used as a reference panel in all flights. This allowed a direct comparison of data taken simultaneously on test and reference panels under identical test conditions.

Boundary layer data were obtained from a pair of rakes mounted at 73% chord on both panels. The section pressure distributions obtained during flight 2 were from pressure belts installed at midspan of each panel. These data sensors and examples of data obtained are shown in Figure 10.

Data were taken at 15 flight conditions during all flights except flight 3a (4 conditions), covering a wide range of cruise operations within the flight envelope of the test airplane (fig. 11). The Corogard application for flight 4 was intended to match the then-reported fleet average roughness of 150 μin , however, it cured at 160 μin . More recent surveys indicate a B737 fleet average roughness of about 130 μin . Severe erosion was simulated for flight 3a by bonding No. 50 grit particles along a 7.6-cm (3-in) strip of the test leading edge. The simulated rough leading edge is compared in Figure 12 with a badly eroded leading edge of an airline transport photographed on the flight line. (The B737 is limited to leading-edge roughness of No. 240 grit equivalent to ensure adequate stall margins in low-speed flight.)

Test Results. Test results were analyzed to determine the effects of coatings on section profile drag at the measurement station and were extrapolated to effects on total airplane drag of the test airplane. The analysis method and extrapolation process are fully described in References 3 and 4.

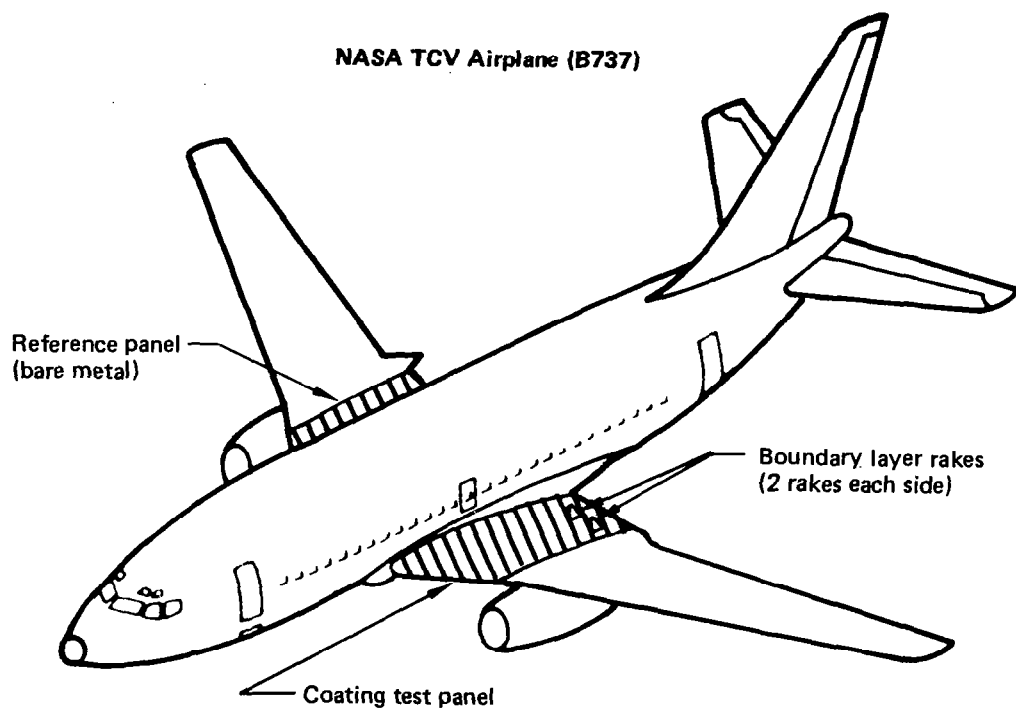
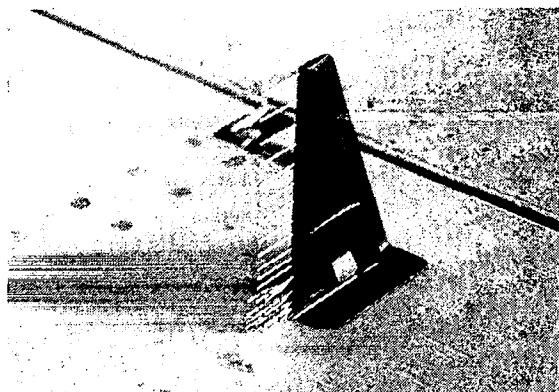
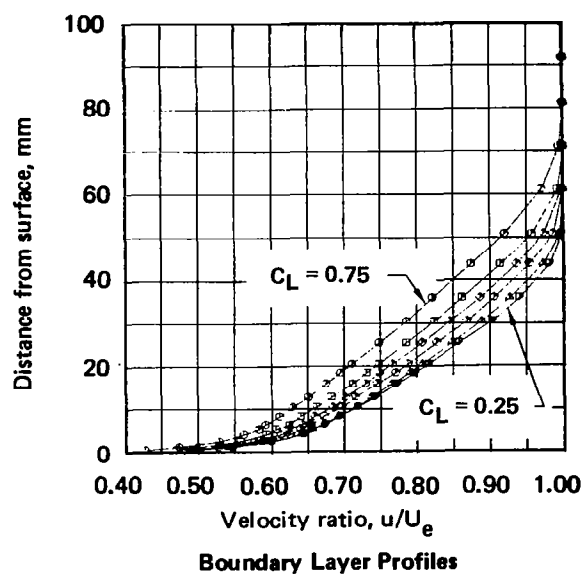


Figure 9. Drag Measurement Test Configuration



Boundary Layer Rake



Pressure Belt

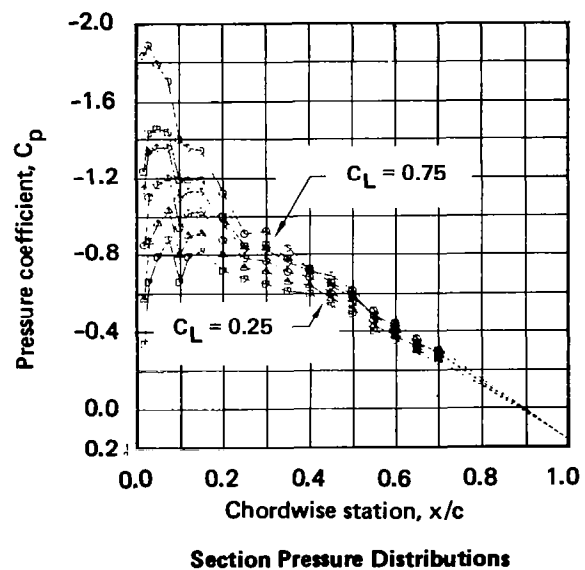


Figure 10. Sensor Installations and Examples of Data Obtained

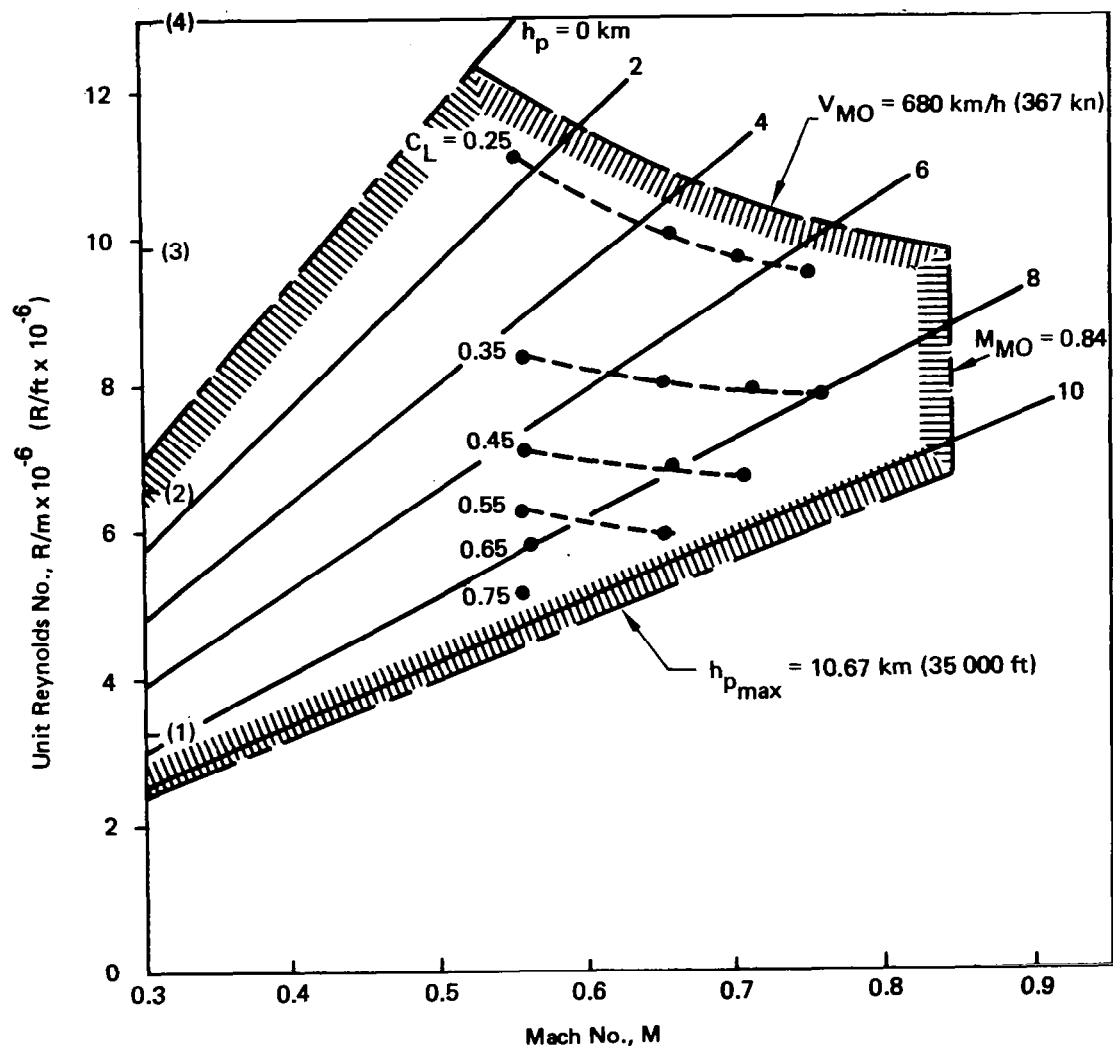
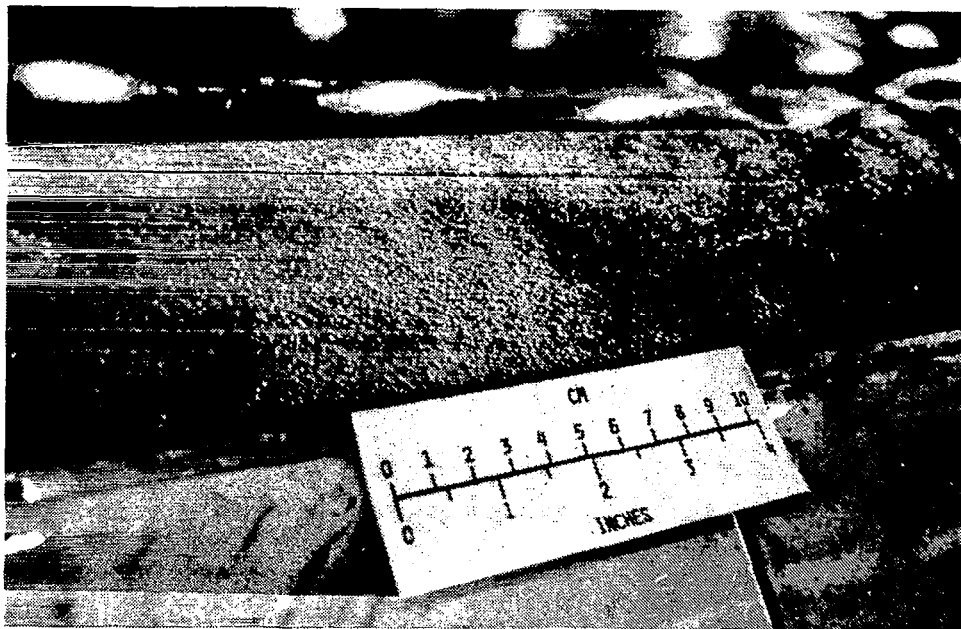
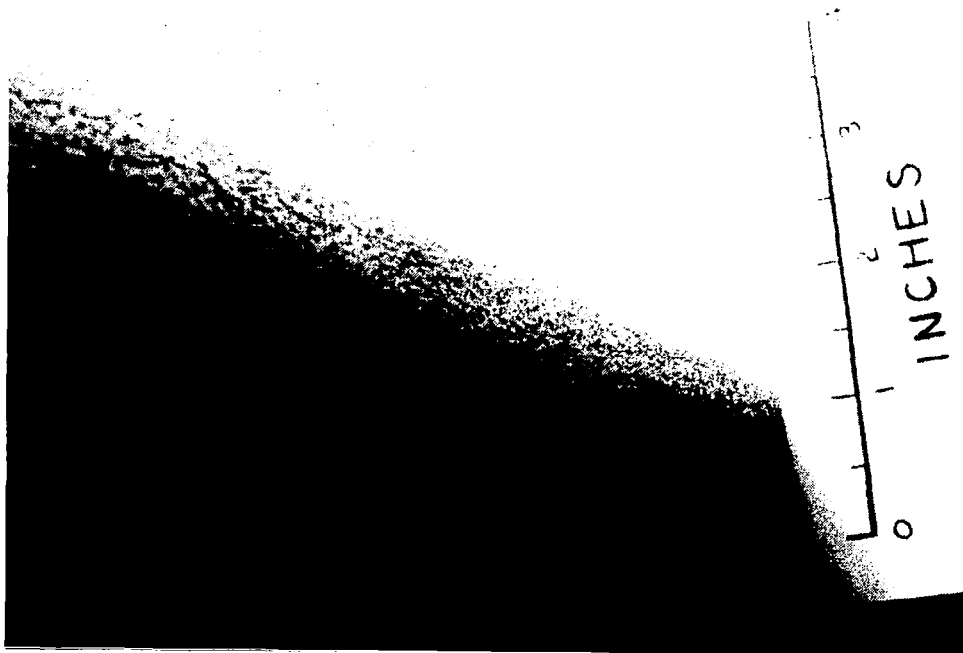


Figure 11. Range of Test Conditions



Simulated
rough leading
edge (flight 3a)



Severe leading-
edge erosion on
airline transport
wing

Figure 12. Comparison of Simulated and Actual Rough Leading Edges

The effects of coatings on section profile drag are shown in Figure 13 as a function of unit Reynolds number. The effects of leading-edge roughness are shown as a function of lift coefficient.

- CAAPCO coating reduced section profile drag 0.75% to 2% relative to the bare reference surface. At a typical cruise Reynolds number of 6.5 million per meter (2 million per foot) the section profile drag reduction is about 1.4% (about 0.2% reduction in total airplane drag, as shown in fig. 14).
- Corogard, which was applied somewhat rougher than normal (160 μin versus an average normal of 130 to 150 μin), produced a section profile drag increase of about 1.2% at cruise. The Corogard drag effects are quite sensitive to Reynolds number. Reynolds number scaling indicates that at roughness levels of 90 to 100 μin in the Corogard, penalty would decrease to zero. As a result of these tests, industry is taking steps to reduce the roughness of Corogard applications.
- The rough leading edge increased section profile drag about 1.5% at cruise lift coefficient ($C_L = 0.45$). Leading-edge roughness effects are quite sensitive to lift coefficient.
- The existing paint produced a slight increase in drag relative to the bare reference surface; however, the results were within the data scatterband and were considered inconclusive.

The effects of coatings and rough leading edge on total drag of the test airplane were estimated from the measured data. Results are summarized in Figure 14. Corogard was treated as a distributed roughness surface, and corrections for variations in area covered along the span were included. CAAPCO and the rough leading edge behaved as if discrete roughness elements were involved, therefore, the drag coefficient increments were assumed to be independent of spanwise location.

- At a typical cruise condition, lift coefficient = 0.45 and Reynolds number = 6.5 million per meter (2.0 million per foot), the total airplane drag increments relative to the bare surface for the test airplane are estimated to be:

CAAPCO	0.2% <u>decrease</u>
Rough Corogard (160 μin)	0.2% <u>increase</u>
Rough leading edge	0.3% <u>increase</u>

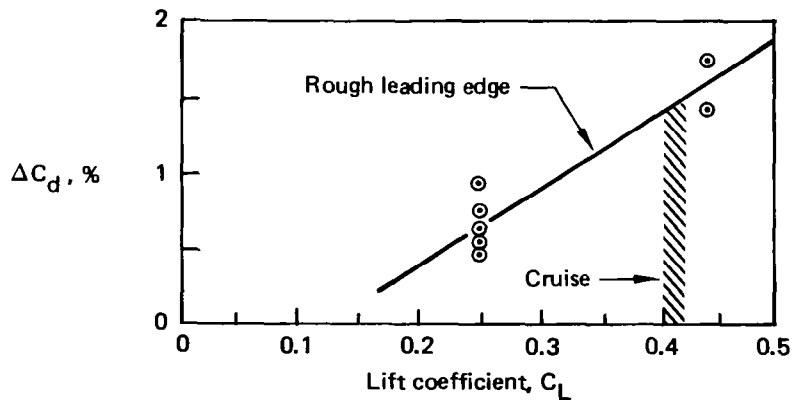
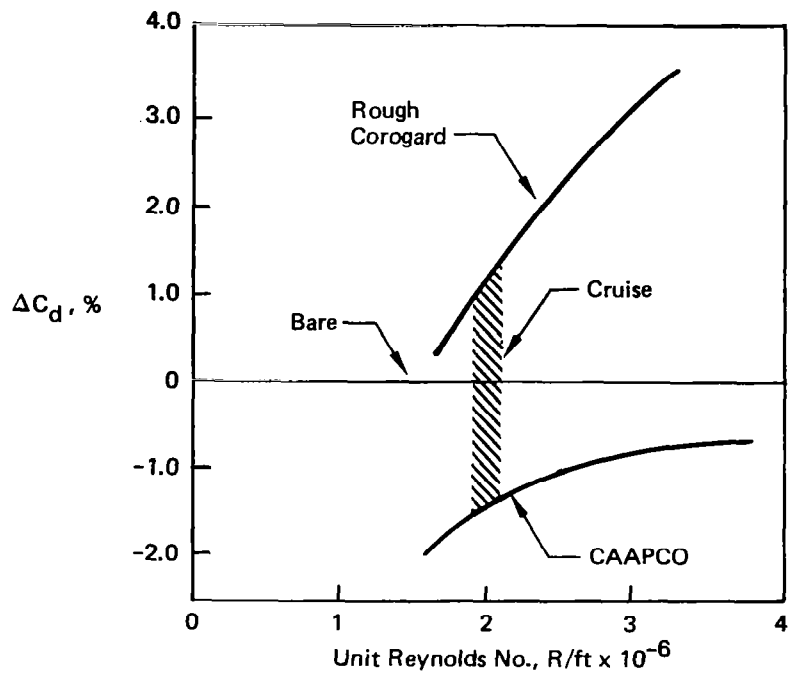


Figure 13. Effect of Coatings and Rough Leading Edge on Section Profile Drag

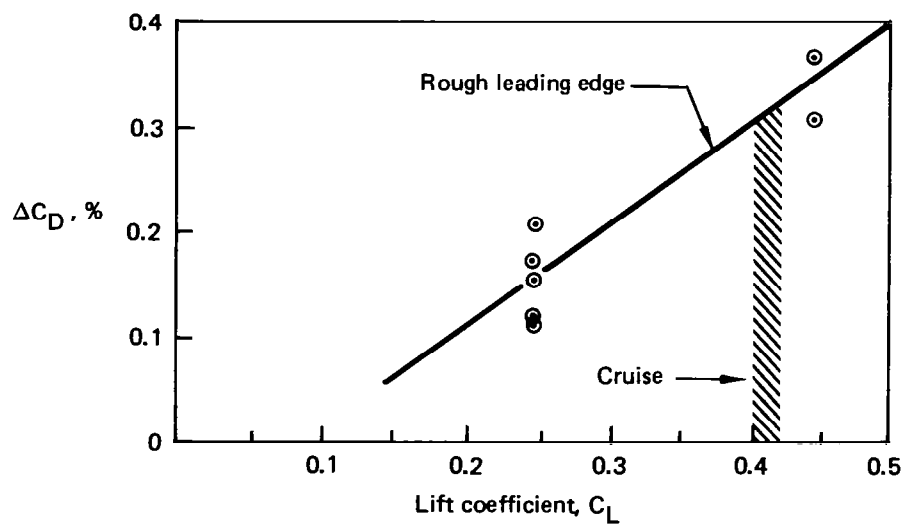
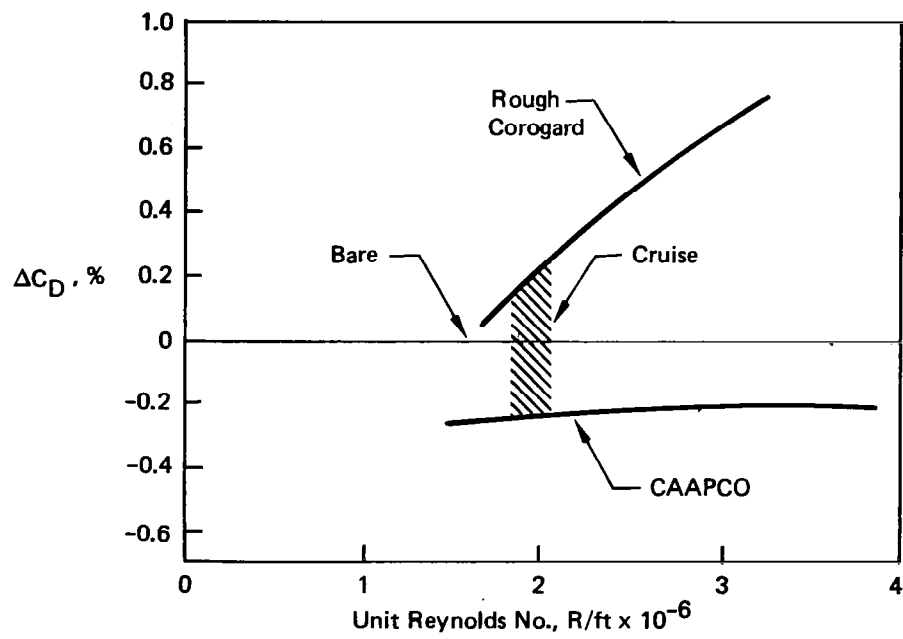


Figure 14. Effect of Coatings and Rough Leading Edge on Total Airplane Drag

COST/BENEFIT ANALYSIS

The economics of using the coatings in airline operations were examined for the B737 with two different coating configurations. Figure 15 shows the two configurations analyzed. Case I had a 9-mil coating of CAAPCO or Chemglaze on the leading edges of wing and empennage surfaces for erosion protection. Benefits from this application were assumed to be a 0.3% drag reduction from maintaining a smooth wing leading edge. No additional credit was taken for smooth empennage leading edges. In case II, a 4-mil coating of CAAPCO or Chemglaze, with a 2-mil topcoat of polyurethane enamel, was added to the inspar areas in place of Corogard on the wing upper surface and in place of enamel on the empennage upper and lower surfaces. Based on the drag measurement tests, a drag reduction of 0.85% was assumed (smooth wing leading edge = 0.3%; smooth wing inspar area = 0.4%; smooth empennage inspar area = 0.15%).

Annual utilization rates of 2400 and 2700 flight-hours were used to cover the experience of various airlines. Based on flight service evaluation results, a leading-edge life of coatings was assumed to be 6500 flight-hours for CAAPCO and 5000 flight-hours for Chemglaze. Life of inspar coatings or standard paint was assumed to be 12 000 hours, equivalent to a major scheduled maintenance interval. Costs of labor, materials, and airplane downtime for coating application were assessed in 1981 dollars. The fuel-burn penalty for added weight of coatings over the standard paint configuration, shown in Figure 16, was included in the analysis.

Results of the cost/benefit analysis are summarized in Figure 17. Applications of coatings to the leading edge only (case I) for erosion protection do not produce a net benefit to the operator from reduced fuel burn until fuel price exceeds 36¢/L (\$1.37/gal) for CAAPCO or 40¢/L (\$1.51/gal) for Chemglaze applications. Some operators with severe erosion problems might benefit from a case I application through other considerations such as reduced costs for leading-edge maintenance and parts replacement or improved low-speed handling characteristics. Case II applications indicate a net annual benefit per airplane of \$10 000 to \$20 000, depending on fuel price and annual utilization. These benefits are based on replacing severely eroded leading edges and rough Corogard with the elastomeric coatings that mask minor substrate excrescences and present a surface smoother than the bare substrate.

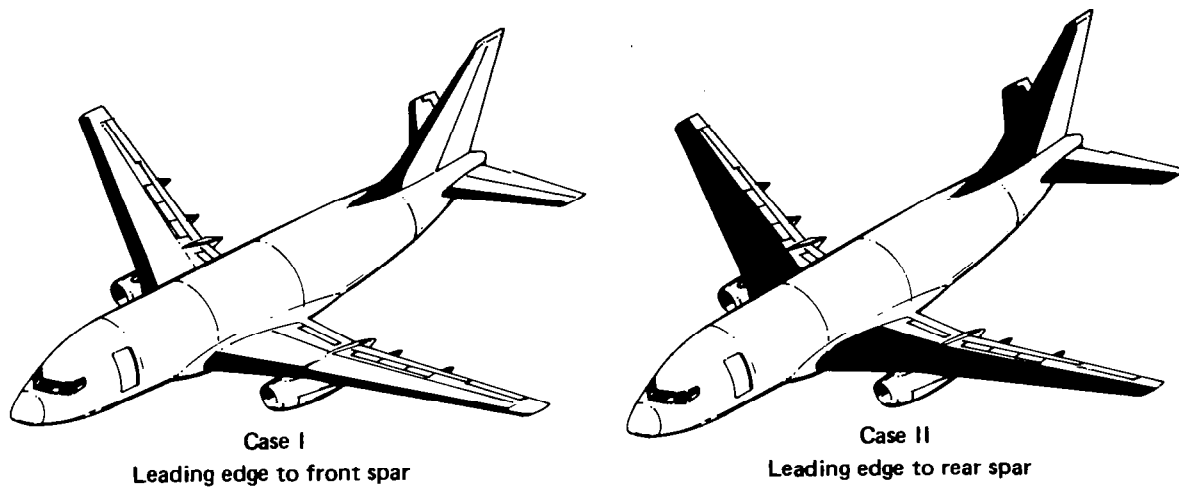


Figure 15. B737 Coating Application Areas

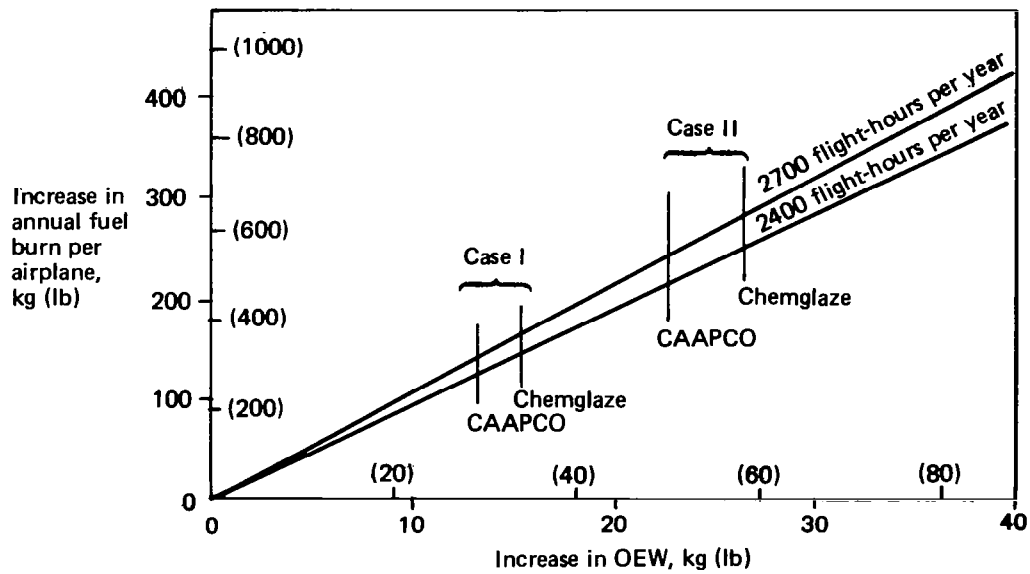
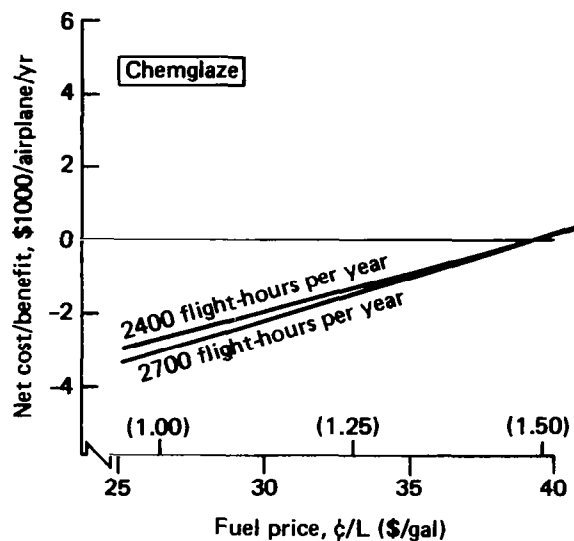
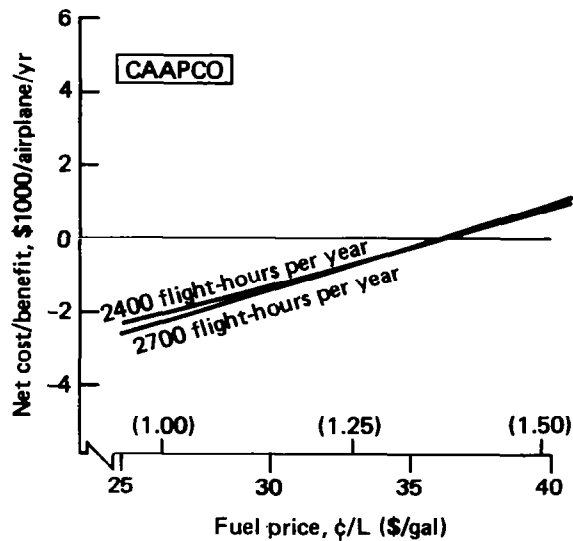
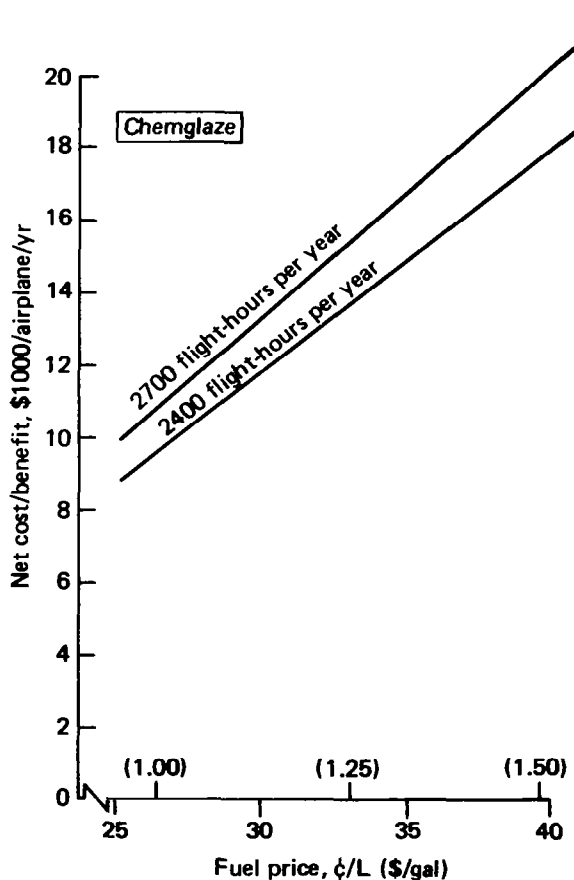
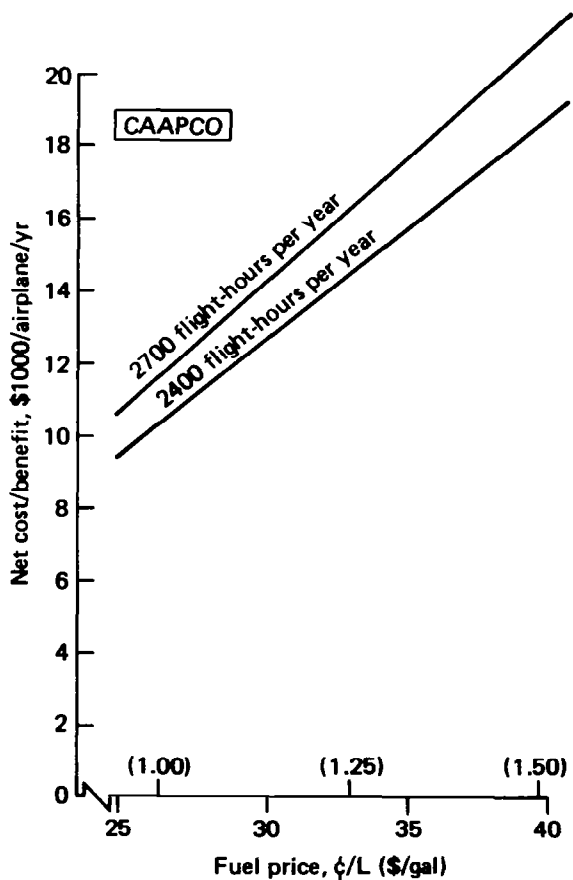


Figure 16. B737 Fuel-Burn Sensitivity to Increase in Weight



(a) Case I—Leading-Edge Coatings



(b) Case II—Coatings from Leading Edge to Rear Spar

Figure 17. Estimated Cost/Benefit of Coatings on a B737

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are drawn from the results of the laboratory testing, service evaluations, flight testing, and cost/benefit analyses of surface coatings:

- It is not economically practical to consider thin films for application to large surfaces, especially those surfaces with compound curvature.
- Liquid spray-on elastomeric polyurethanes have superior erosion-resistance qualities. CAAPCO B-274 and Chemglaze M313 had the greatest durability of the materials tested. CAAPCO is more resistant to synthetic-type hydraulic fluid than Chemglaze.
- Manufacturers' application procedures should be followed rigorously. It is essential for good adhesion that the substrate be thoroughly cleaned prior to application.
- CAAPCO requires an epoxy primer for best adhesion. Either a wash primer or an epoxy primer can be used with Chemglaze.
- A dual coating of 4 mil of CAAPCO, Chemglaze, or Astrocoat, with a 2-mil topcoat of polyurethane enamel, provided good corrosion protection to structural substrate surfaces in laboratory tests. The enamel topcoat gives added protection against hydraulic fluid exposure, but is not durable under high-impact erosion. The use of dual coatings, therefore, should be restricted to areas aft of the front spar.
- CAAPCO or Chemglaze coatings on thermally anti-iced leading edges will not significantly degrade anti-icing system performance. The coatings are compatible with the elevated temperatures produced in these areas.
- A 9-mil leading-edge coating and a 6-mil dual coating between spars will not cause precipitation static interference with communication and navigation equipment.
- The possible effects of coatings on lightning attachment patterns should be analyzed for areas containing wing fuel above wing-mounted engines.
- It was estimated from flight test results that coatings, in place of rough Corogard on wing upper surfaces of a B737 and enamel on empennage surfaces would reduce total airplane drag about 0.55%. A severely eroded wing leading edge produces a drag penalty of about 0.3%. With fuel at 26.4¢/L (\$1.00/gal), the total net benefit for a B737 airplane per year would be about \$10 000.

The following recommendations are made:

- Airlines that experience severe leading-edge erosion problems should apply a 9- to 12-mil coating of CAAPCO B-274 (or as an alternative, Chemglaze M313) to leading-edge areas. The benefits could include reduced drag, reduced costs for maintenance and parts replacement, and improved low-speed handling qualities.

- Laboratory tests showed dual coatings to be effective in protecting the substrate against corrosion. Flight tests showed a drag benefit. Therefore, industry should pursue any additional corrosion protection investigations necessary to fully qualify these coatings for application to the wing and empennage inspar areas of the jet transport fleet.

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16. Abstract <p>This report summarizes a series of studies in which films and liquid spray-on materials were evaluated in the laboratory for transport aircraft external surface coatings. Elastomeric polyurethanes were found to best meet requirements. Two commercially available products, CAAPCO B-274 and Chemglaze M313, were subjected to further laboratory testing, airline service evaluations, and drag-measurement flight tests.</p> <p>It was found that these coatings were compatible with the severe operating environment of airlines and that coatings reduced airplane drag. An economic analysis indicated significant dollar benefits to airlines from application of the coatings.</p>					
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